SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
Annual report for work on "Cooled Ion Frequency Standard"
ONR Contract-N00014-89-F-0001

5. TYPE OF REPORT & PERIOD COVERED
Annual Oct. 1,88-Sept. 31,'89

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
D.J. Wineland

8. CONTRACT OR GRANT NUMBER(s)
ONR Contract No. N00014-89-F-0001

9. PERFORMING ORGANIZATION NAME AND ADDRESS
National Institute of Standards & Technology
Time and Frequency Division 576
Boulder, CO 80303

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Office of Naval Research
Physics Program Office 800 N. Quincy
Arlington, VA 22211

12. REPORT DATE
9-10-89

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release: distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Atomic spectroscopy; Doppler narrowing; Doppler shifts; frequency standards; high resolution spectroscopy; ion storage; laser spectroscopy; Penning trap; laser cooling

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
The purpose of this work is to develop techniques to overcome the fundamental limits of present frequency standards--the second order and residual first-order Doppler shifts. To this end we ~~study~~ suitable frequency reference transitions in ions which are stored on electromagnetic traps and cooled by radiation pressure to less than 1K.

Summary of Work on

"COOLED ION FREQUENCY STANDARD"

(FY 89)

submitted to

Office of Naval Research

ONR Contract No. N00014-89-F-0001

Project Leader:

D.J. Wineland

Frequency & Time Standards Group

576.11

National Bureau of Standards

Boulder, Colorado 80303

FTS: 320-5286

(303) 497-5286

Contract Description

The purpose of this work is to develop techniques to overcome the fundamental limits of present methods for high resolution spectroscopy and frequency standards--the second order and residual first-order Doppler shifts. To this end, we study suitable frequency reference transitions in ions which are stored in electromagnetic traps and cooled by radiation pressure to < 1K.

Scientific Problem

The scientific problems are (1) to suppress second order and residual first order Doppler shifts in atomic spectroscopy in a fundamental way--by substantially reducing the kinetic energy of ions stored ion electro-magnetic traps, (2) to study suitable reference transitions in ions that can be used as frequency standards, and (3) to study the problems (i.e., systematic effects) generic to all stored ion frequency standards. The goal is to achieve at least a factor of 100 improvement in accuracy over the present best device, the Cesium beam frequency standard, which has an accuracy of approximately 2 parts in 10^{14}.

Scientific and Technical Approach

Laser cooling is employed on all experiments in order to suppress Doppler shifts. Temperatures as low as 40 μK have been achieved and temperatures less than 0.1K are routinely achieved. To avoid light shifts on "clock" transitions we investigate "sympathetic cooling" where one ion species is laser cooled and by Coulomb collisions cools another ion species of spectroscopic interest. We continue experiments on Mg^+ and Be^+ in order to study generic problems with traps since these ions are easier to laser cool. We are developing a separate experiment for Hg^+ ions. These experiments have the goal of realizing a frequency standard with 10^{-15} or better accuracy.

III. PROGRESS DURING LAST CONTRACT PERIOD

Summary of progress since Oct. 1, '88. (details start on p.5)

(1.) *$^9Be^+$ frequency standard.* An oscillator has been locked to a nuclear spin flip hyperfine transition ($\simeq$ 303 MHz) in $^9Be^+$ ions which are stored ion a Penning trap. Recent experiments have employed "sympathetic laser cooling" whereby laser cooled Mg^+ ions are stored simultaneously with the Be^+ ions and the Coulomb interaction between ions cools the Be^+ ions. This has allowed the hyperfine transition to be interrogated with Ramsey times of up to 550 s giving linewidths less than 0.001 Hz. Stabilities (which are currently limited by the reference clock) are measured to be better than $3\times10^{-12}\tau^{-1/2}$. Uncertainties in Doppler effects are estimated to be less than 5×10^{-15}. For comparison, the smallest uncertainty previously claimed for Doppler shifts on any atomic clock is 15×10^{-15} (cesium, PTB, West Germany).

(2.) *Hg^+ optical frequency standard*: A stable laser has been used to probe the $5d^{10}6s\ ^2S_{1/2} \rightarrow 5d^9 6s^2\ ^2D_{5/2}$ transition in $^{199}Hg^+$. Linewidths of approximately 100 Hz have been observed giving a quality factor $Q \equiv \nu_0/\Delta\nu(\text{linewidth}) \simeq 10^{13}$. This is the highest Q ever reported in atomic or molecular spectroscopy.

(3.) *Optical sideband cooling experiments completed*: The fundamental limit of cooling for any particle which is contained by some apparatus (the electrodynamic trap in our experiment, or the walls of the vacuum apparatus in a neutral atom experiment) is putting the atom in the zero point state of motion. We have achieved this (for the first time) using single Hg^+ ions and published a paper in Phys. Rev. Lett.

(4.) *Test of the linearity of Quantum Mechanics.* A hyperfine transition in the ground state of $^9Be^+$ was used to test a nonlinear generalization of quantum mechanics recently formulated by Weinberg. We searched for a dependence of the frequency of a coherent superposition of two hyperfine states on the populations of the states. We are able to set a limit of 4×10^{-27} on the fraction of binding energy per nucleon of the $^9Be^+$ nucleus that could be due to nonlinear corrections to quantum mechanics. This is five orders of magnitude better than the previous best estimate.

(5.) *Search for anomalous long range interactions by $^9Be^+$ nuclear magnetic resonance.* We have searched for interactions which could arise if the $^9Be^+$ nucleus has a gravitational dipole moment or has an anomalous long range spin-spin interaction. Such experiments are the spin dependent counterparts of "fifth force experiments."

(6.) *Preliminary observations of quantum Zeno effect.* The quantum Zeno effect is the inhibition of transitions by frequent measurements. We have observed this effect in a ground state hyperfine transition of $^9Be^+$ ions.

(7.) *Sympathetic cooling.* Sympathetic laser cooling has been now routinely used to cool $^9Be^+$ ions (sympathetically cooled by laser cooled Mg^+ ions). This has allowed observation of linewidths as small as 0.0003 Hz, the <u>smallest recorded in atomic or molecular spectroscopy</u>.

(8.) *Synchrotron frequency divider.* Trap construction complete, almost ready for installation in vacuum.

(9.) *Laser development.* Effort has been devoted to stabilizing a dye laser (563 nm) to a Fabry-Perot cavity. (This laser, when doubled, is used to probe the optical "clock" transition in Hg^+) stabilities/spectral widths of 50 Hz obtained for > 1 minute. This <u>linewidth is narrower than any visible laser ever reported</u>.

(1.) Be^+ Frequency Standard

In this experiment, an oscillator has been locked to the (m_I = -1/2, m_J = 1/2) ⟷ (-3/2, 1/2) nuclear spin flip hyperfine "clock" transition ($\omega_0/2\pi$ ≈ 303 MHz) in the ground state of $^9Be^+$. (Fig. 1)

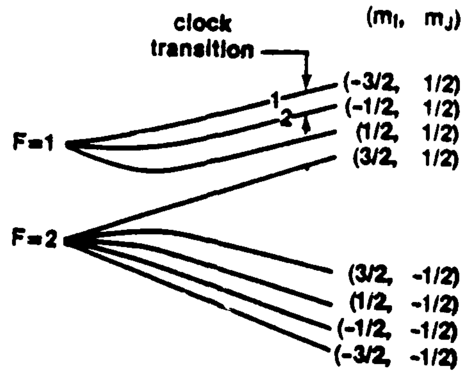

Fig. 1. Hyperfine energy levels (not drawn to scale) of the $^9Be^+$ 2s $^2S_{1/2}$ ground state as a function of magnetic field. At B = 0.8194 T the 303 MHz clock transition is independent of magnetic field to first order.

The basic idea of this experiment is as follows: between 5000 and 10 000 $^9Be^+$ ions and 50 000 to 150 000 $^{26}Mg^+$ ions were simultaneously stored in a cylindrical Penning trap with B ≈ 0.8194 T under conditions of high vacuum ($\lesssim 10^{-8}$ Pa). At a magnetic field B of 0.8194 T the clock transition depends only quadratically on magnetic field fluctuations and therefore the accuracy is not limited by field fluctuations. To minimize second order Doppler shifts of the clock transition, the $^9Be^+$ ions were cooled to less than 250 mK. The $^{26}Mg^+$ ions were directly laser cooled and compressed by a narrow band (~ 1 MHz) laser radiation source at 280 nm. The $^9Be^+$ ions were then sympathetically cooled by their Coulomb interaction with the cold Mg^+ ions. A narrow band 313 nm radiation source was used to optically pump and detect the $^9Be^+$ ions. With the 313 nm source tuned to the 2s $^2S_{1/2}$ (m_I = 3/2, m_J = 1/2) to 2p $^2P_{3/2}$(3/2, 3/2) transition, 94% of the $^9Be^+$ ions were optically pumped into the 2s $^2S_{1/2}$(3/2, 1/2) ground state. The 313 nm source was then turned off to avoid optical pumping and ac Stark shifts. The sympathetic cooling of the $^9Be^+$ ions by the continuously cooled Mg^+ ions provided a steady cooling source independent of the 313 nm radiation and therefore permitted the use of long transition times.

The clock transition was detected by the following method. After the 313 nm source was turned off, the ions in the (3/2, 1/2) state were transferred to the (1/2, 1/2) state and then to the (-1/2, 1/2) state by two successive rf π pulses. Each pulse was 0.2 s long and resonant with the appropriate transition frequency (around 321 MHz and 311 MHz respectively). The clock transition was then driven by Ramsey's method of separated oscillatory fields with rf pulses of about 1 s duration and a free precession time on the order of 100 s. This transferred some of the ions from the (-1/2, 1/2) state to the (-3/2, 1/2) state. Those ions remaining in the (-1/2, 1/2) state were then transferred back to the (3/2, 1/2) state by reversing the order of the two rf π pulses. The 313 nm source was then turned back on, and the popul tion of ions in the (-3/2, 1/2) state was registered as a decrease in the $^9Be^+$ fluorescence, relative to the steady-state fluorescence, during the first second that the 313 nm source was on. (The optical repumping time of the ions from the (-3/2, 1/2) state to the (3/2, 1/2) state was an order of magnitude longer than this.)

The Ramsey signal was used to steer the frequency of a synthesized rf source. Ramsey signal measurements were taken near both of the full-width-at-half-maximum frequencies. The difference in the measured signal strengths on either side of the line center was used to electronically steer the average frequency of the synthesizer to ω_o. Most runs were taken with a commercial cesium beam clock (fractional frequency stability $\sigma_y(\tau) \sim 6\times10^{-12}\tau^{-\frac{1}{2}}$ for measurement time τ in seconds) as the reference oscillator, but a few runs were taken with a passive hydrogen maser ($\sigma_y(\tau) \sim 2\text{-}3 \times 10^{-12}\tau^{-\frac{1}{2}}$) as the reference oscillator. The stability of the $^9Be^+$ clock was measured to be less than $3 \times 10^{-12}\ \tau^{-\frac{1}{2}}$ for the number of ions used. The systematic error of our measurement of ω_o due to the second order Doppler frequency shiftt is 5×10^{-15}. This is three times smaller than ever reported for Doppler frequency shifts. We are continuing to search for other causes of systematic errors such as pressure shifts due to collisions with background gas; however, we feel the accuracy could be significantly improved beyond 5 parts in 10^{15} in the future.

(2.) Hg^+ Optical Frequency Standard

The velocity in the micromotion for ions in a quadrupole rf trap is proportional to the distance the ion is from the center of the trap. For two or more laser-cooled ions in the trap, the Coulomb repulsion between ions holds them away from the trap center and the second order Doppler shift is dominated by the velocity of micromotion. However, a single ion can be held near the trap center if sufficiently cooled. In this case the kinetic energy in the micromotion is equal to that of the secular motion. If the ion is laser cooled, resulting Doppler shifts can be extremely small; uncertainties can be less than 1 part in 10^{20} in the case of sideband cooling (see (3) below). However with N = 1, stability is marginal unless we make ω_o high enough. One way to accomplish this is to let ω_o correspond to an optical transition. The reason that a clock based on an optical transition in an ion has not been realized yet is (1) it took several years to isolate and reliably manipulate single ions in the traps, (2) local oscillators (lasers) with the desired spectral purity are still not available, and (3) accurate comparison of laser and microwave frequencies is at best extremely difficult and remains an important problem. Nevertheless the potential accuracy of single ion optical frequency standards is extremely high so that it is reasonable to pursue this research.

At NIST we have investigated the use of the $5d^{10}6s\ ^2S_{½} \rightarrow 5d^9 6s^2\ ^2D_{5/2}$ electric quadrupole transition ($\omega_o/2\pi \simeq 1.07 \times 10^{15}$ Hz) in $^{198}Hg^+$ (see Fig. 2) as an optical frequency standard. The single mercury ion is confined in a miniature rf trap that has internal dimensions of $r_o \simeq 466$ μm and $z_o \simeq 330$ μm. The amplitude of the trapping field (frequency $\Omega/2\pi \simeq 21$-23 MHz) could be varied to a peak of 1.2 kV. The ion is laser cooled to a few millikelvins by a few microwatts of cw laser radiation

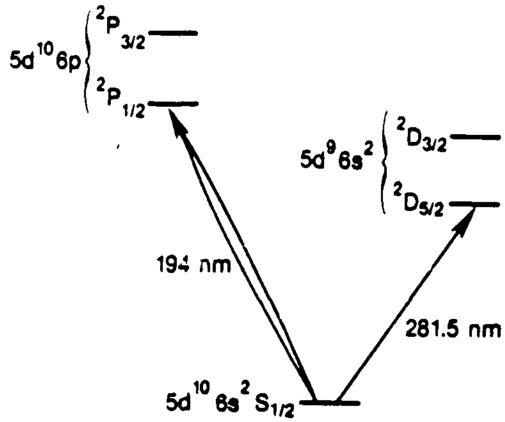

Fig. 2. Simplified optical energy-level diagram for Hg^+. The lifetime of the $^2D_{5/2}$ level is about 0.1 s which would give a linewidth of 2 Hz on the electric quadrupole $^2S_{1/2} \rightarrow {}^2D_{5/2}$ transition. By observing the presence of or lack of fluorescence from the $^2S_{1/2} \rightarrow {}^2P_{1/2}$ transition, the quadrupole "clock" transition can be detected with 100% efficiency.

that is tuned below the $^2S_{1/2}$ - $^2P_{1/2}$ first resonance line near 194 nm. In order to cool all motional degrees of freedom to near the Doppler cooling limit ($T = \hbar\gamma/2k_B \simeq 1.7$ mK) the 194 nm radiation irradiates the ion from 2 orthogonal directions, both of which are at an angle of 55° with respect to the symmetry (z) axis of the trap. The 282 nm radiation that drives the narrow $^2S_{1/2}$ - $^2D_{5/2}$ transition is obtained by frequency-doubling the radiation from a narrowband cw ring dye laser. In the long term, the laser is stabilized by FM optical heterodyne spectroscopy to a saturated absorption hyperfine component in $^{129}I_2$. The frequency of the laser is scanned by an acousto-optic modulator that is driven by a computer controlled synthesizer. Up to a few microwatts of 282 nm radiation could be focussed onto the ion in a direction counterpropagating with one of the 194 nm light beams.

Optical-optical double resonance was used to detect transitions driven by the 282 nm laser to the metastable $^2D_{5/2}$ state. The 194 nm fluorescence rate from the laser-cooled ion is high when the ion is cycling between the $^2S_{1/2}$ and $^2P_{1/2}$ levels (Fig. 2) and nearly zero when it is in the metastable $^2D_{5/2}$ state. Thus the $^2S_{1/2}$ - $^2D_{5/2}$ resonance spectrum was obtained by probing the S-D transition at a particular frequency for the 282 nm radiation for 20 ms, then turning off the 282 nm radiation and turning on the 194 nm radiation to look for the presence or absence of scattered photons at 194 nm (the two radiation fields are alternately applied to avoid light shifts and broadening of the narrow S-D transition). If there was no fluorescence at 194 nm, a transition into the metastable D state had occurred; the presence of 194 nm fluorescence indicated that the ion was in the ground state and no transition was recorded for this frequency of the 282 nm laser. The frequency was then stepped and the measurement cycle repeated. As the frequency was stepped back and forth each new result at a particular frequency of the 282 nm radiation was averaged with the previous measurements at that frequency. Normalization (or quantization) of the signal was obtained by assigning a 1 to each measurement of high fluorescence and a 0 to each measurement of no fluorescence. The high fluorescence level made it possible to determine the state of the atom with almost no ambiguity in a few milliseconds. Thus, it is easy to reach the shot noise limit imposed by the single atomic absorber.

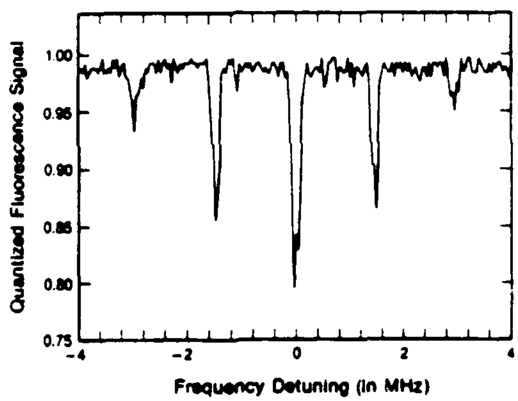

Fig. 3. The quantized fluorescence signal obtained from an 8-MHz scan of the 282 nm laser through the $^2S_{1/2}(m_J = -1/2) \rightarrow {}^2D_{5/2}(m_J = 1/2)$ Zeeman component of the electric quadrupole transition is shown in Fig. 3. The recoilless-absorption resonance (carrier) and the motional sidebands due to the secular motion in the harmonic well of the rf trap are completely resolved.

To avoid broadening of the quadrupole transition due to magnetic field fluctuations, we have recently performed essentially the same experiment on the $^2S_{1/2}(F=0,\ m_F=0) \rightarrow {}^2D_{5/2}(F=2,\ M_F=0)$ transition in $^{199}Hg^+$ which becomes field independent as $B \rightarrow 0$. The carrier is now observed with a linewidth $\Delta\nu \approx 100$ Hz (limited by laser spectral purity), which gives <u>a</u>

line Q of about 10^{13}, the highest reported in atomic or molecular spectroscopy. Current efforts are devoted to improving the 282 nm laser spectral purity by locking it to a more stable reference cavity (see proposed work). If the laser spectral purity can be made high enough, then when the laser is locked to the ion transition, stabilities are anticipated to be better than $10^{-15}\tau^{-1/2}$ and accuracies could be 1 part in 10^{15} or better.

(3.) Optical Sideband Cooling and the Fundamental Limit of Laser Cooling Achieved.

In all laser-cooling experiments performed to date, cooling has been accomplished in the regime where the oscillation or vibration frequency ω_v of the particle in its confining well was less than the natural width γ of the cooling transition. This regime also applies to "free" atom cooling experiments such as optical molasses ($\omega_v \rightarrow 0$). In recent experiments by us, laser-cooling in the sideband limit (where $\omega_v > \gamma$) was accomplished for the first time. Using this technique, a single trapped Hg^+ ion was cooled such that it spent most of its time in the ground state quantum level of the confining potential. To the extent that the ion is in the zero point energy state of motion, this realized for the first time the fundamental limit of laser cooling and the ideal of an isolated atomic particle at rest in free space to within the quantum mechanical limits imposed by the surrounding apparatus.

The ion was confined in a Paul(rf) trap and first cooled to near the "Doppler cooling limit" of $T = \hbar\gamma/2k_B \simeq 1.7$mK by scattering 194 nm photons on the strong $^2S_{1/2}$ - $^2P_{1/2}$ dipole transition. In a second step, the 194 nm radiation was switched off and the $^2S_{1/2}$ - $^2D_{5/2}$ quadrupole transition at 282 nm was driven on the resolved first lower secular motion sideband frequency by a narrowband dye laser with an intensity of approximately 10 W/cm^2. This radiation was derived from a frequency doubled dye laser. The radiation bandwidth at 282 nm was approximately 40 kHz. In order to enhance the speed of the sideband cooling, the 90 ms lifetime of the $^2D_{5/2}$ state was reduced by driving the $^2D_{5/2}$ - $^2P_{3/2}$ dipole transition (λ = 398 nm) by another frequency doubled dye laser.

From the $^2P_{3/2}$ state, the ion rapidly decays to the $^2S_{½}$ ground state. The kinetic energy of the ion after cooling was probed by measuring the excitation probability of the $^2S_{½}$ - $^2D_{5/2}$ transition at the carrier and at the sideband frequencies.

In a first experiment, the potential well was nonspherical and only the axial motion at $\omega_v/2\pi$ = 4.66 MHz was cooled below the Doppler cooling limit. After cooling, the excitation rate on the first upper sideband (Stokes transition) at frequency $\omega_0 + \omega_v$ was twenty times stronger than on the first lower (anti-Stokes) sideband. This indicates that the ion is in the ground state ($n_v = 0$) level of motion after cooling approximately 95% of the time.

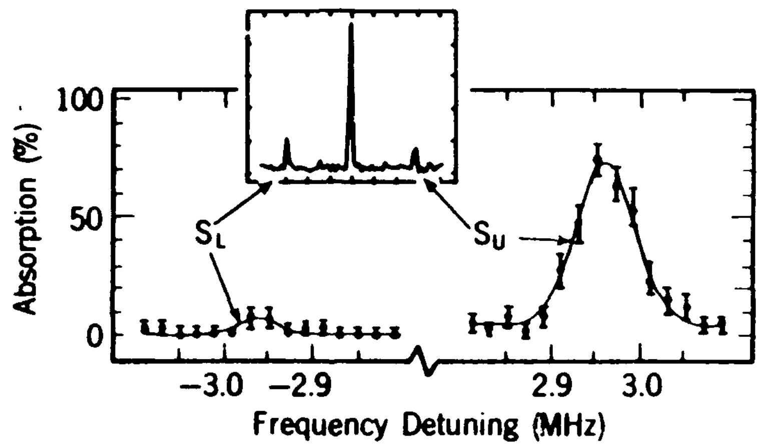

Fig. 4. Absorption spectrum of the $^2S_{½}$ - $^2D_{5/2}$ electric quadrupole transition of $^{198}Hg^+$. The inset spectrum was taken before sideband cooling was applied. It shows the carrier at zero detuning (frequency ω_0) and the first sidebands (at frequencies $\omega_0 - \omega_v$ and $\omega_0 + \omega_v$) generated by the ion's motion in the approximately spherical well. For this spectrum, the bandwidth of the 282 nm radiation was broadened to 120 kHz to reduce the number of required data points and the laser power was reduced in order to avoid saturation. The enlarged part of the figure shows the absorption strength S_L (S_U) on the lower (upper) motional sideband 15 ms after the end of the sideband cooling. Values for S_L and S_U were obtained from Gaussian fits to the data points which are averaged over 41 sweeps.

In a second experiment, the ion was kept in an approximately spherical potential well (secular frequencies ≈ 2.95 MHz) and all degrees of freedom were cooled to near 1.7 mK by two orthogonal beams of 194 nm radiation. From the fixed spatial orientation along the "x" axis of two laser cooled ions in the trap it is known that the radial frequencies are nondegenerate. Thus a single 282 nm beam directed at an angle so that it is not perpendicular to any of the trap axes and overlapped in frequency with the first lower nondegenerate sidebands cools all degrees of freedom simultaneously. Figure 4 shows the absorption spectrum on the quadrupole transition after sideband cooling. From this data we determine that the ion is in the ground state of motion 95% of the time and the equivalent temperature of the ion is about 45 μK.

For our data, the uncertainty in the second-order Doppler shift is dominated by the uncertainty in $\langle n_v \rangle$ and amounts to $\Delta\nu/\nu < 10^{-20}$. It can be made substantially lower by adiabatically lowering the potential well depth after the ion is cooled into the ground state. With our experiment, the absorption of a single quantum of energy at a (tunable) frequency in the MHz range can be detected with an efficiency of nearly 100% as indicated by the appearance of the lower sideband. With appropriate coupling to the ion's motion (for example, via one of the endcaps), a similar apparatus could serve as a very sensitive spectrum analyzer. In another possible application, the motion of a trapped charged particle could be damped by coupling it electronically to a second laser-cooled ion in a separate trap, thereby reducing the first charged particle's kinetic energy to near the zero-point energy. Resonant excitation of the first particle' motion could then be detected very sensitively by its influence on the laser-cooled ion. Such a device might be useful in mass spectroscopy.

(4.) Test of the linearity of Quantum Mechanics.

Recently, Weinberg has proposed a nonlinear generalization of quantum mechanics (Phys. Rev. Lett. 62, 485 (1989)). He suggested that a sensitive test could be made for the presence of such a nonlinearity by slowly driving a resonant transition from one state to another. The effect of the nonlinearity is to make the effective resonance frequency a function of the state probabilities. Thus, the resonance frequency changes as the quantum system is driven from one state to the other, and the applied perturbation (assumed to be monochromatic) cannot stay in resonance through the entire transition. The system will never be driven completely to the other state. This effect would not be observed, that is, the transition could still be driven, if the maximum frequency shift were much less than 1/T. Here, T is the time required to drive the transition if there is no nonlinearity. Since such transitions have been observed with T as long as ~ 1 s, one can set a limit ~ 10^{-15} eV on the magnitude of such nonlinear corrections to quantum mechanics.

In the present work, we perform a more sensitive test by looking directly for a change in the precession frequency of a two-level system as a function of the admixture of upper and lower states. $^{9}Be^{+}$ ions are stored in a Penning trap and sympathetically cooled and compressed by laser-cooled $^{26}Mg^{+}$ ions. The $(m_I, m_J) = (-1/2, +1/2) \rightarrow (-3/2, +1/2)$ "clock" transition of the $^{9}Be^{+}$ ground state is chosen as the two level system; its transition frequency of $\nu \simeq 303$ MHz is magnetic field-independent to first order at the field $B \simeq 0.8194$ T. The transition frequency is probed using Ramsey's method of separated oscillatory fields, with free precession times as long as 550 s, giving a linewidth of 900 μHz and a line Q of 3.3×10^{11}. The second Ramsey RF pulse has an angle of $\pi/2$, as usual, but the angle of the first RF pulse alternates between $\theta_A = 0.3125\pi$ and $\theta_B = 0.6875\pi$, thus preparing differing initial admixtures. The frequency of a reference oscillator is then locked to the $^{9}Be+$ precession frequency, and the data are analyzed for a difference in the precession frequency with initial pulse angle θ_A from that with initial pulse angle θ_B.

For the $^{9}Be^{+}$ nuclear spin of $I = 3/2$, any nonlinear correction to the precession frequency of the "clock" transition is expected to have the form $\omega(\theta) = 4\epsilon\cos^2(\theta/2)$, where $\cos^2(\theta/2)$ is the fraction of the population in the $(m_I, m_J) = (-1/2, 1/2)$ state and θ may be taken as the angle of the first Ramsey RF pulse. We are currently able to set an upper limit on the magnitude of the parameter ϵ of $|\epsilon| < 2 \times 10^{-20}$ eV (5 mHz). This is less than 1 part in 10^{26} of the binding energy per nucleon of the ^{9}Be nucleus, and about 5 orders of magnitude more sensitive than the result quoted in Weinberg's paper. We have recently submitted a paper reporting this result.

(5.) Search for anomalous long range interactions by $^9Be^+$ nuclear magnetic resonance.

Certain theoretical frameworks allow the possibility of long range scalar, dipole, and higher order tensor interactions which are outside the realm of currently known forces. (J. E. Moody and F. Wilczek, Phys. Rev. D30,130(1984); D. Chang, R. N. Mohapatra, and S. Nussinov, Phys. Rev. Lett. 55,2935(1985) Independent of the specific theory, it is useful to experimentally test for such anomalous couplings if the precision is sufficiently high.

We have recently searched for a coupling of a spin (beryllium nucleus, I=3/2) to:

(a) a preferred reference frame (a test of Local Lorentz Invariance known as a Hughes-Drever experiment) by searching for a variation of the beryllium nuclear precession frequency in a magnetic field as a function of the angle between the magnetic field direction and a preferred direction in space (e.g., the fixed stars). This is a repeat of a previous experiment performed by us but with increased sensitivity.

(b) some nearby mass (e.g., the earth) by looking for an interaction of the form $\vec{\sigma}(Be)\cdot\hat{r}$ where $\hat{r}$ is the direction from the spin to the nearby mass, and

(c) a macroscopic polarization provided by the polarized electrons in the pole faces of a magnet which provides the quantizing magnetic field. Such an interaction would show up as a difference between the nuclear resonance frequency measured in a conventional electromagnet and the frequency measured in a superconducting magnet.

Experiments (b) and (c) can be regarded as the monopole-dipole and dipole-dipole counterparts to the "fifth force" experiments. The precision on these experiments meets or exceeds the precision of experiments which test for such effects (see the above references, plus A. A. Ansel'm and Yu. I. Neronov, Zh. Eksp. Teor. Fiz. 88 1946(1985) (Sov. Phys. JETP 61,1154(1985)).

The beryllium nuclear resonance is due to a 303 MHz nuclear spin flip hyperfine transition in the ground state of atomic Be^+. The ions are stored in an electromagnetic trap for periods as long as a day. The technique of laser cooling is used to reduce the temperature of the ions to less than 1 K thereby minimizing second order Doppler shifts. To within the experimental precision of approximately 50 μHz (2×10^{-19} eV), no evidence for any of the above mentioned couplings is found. A paper on these subjects is in preparation.

(6.) Preliminary observations of quantum Zeno effect.

Laser-cooled ions stored in Penning traps are nearly free from collisions and other perturbations that could cause relaxations. This, and the fact that their energy levels can easily be manipulated with rf and laser radiation, makes them well suited for demonstrating certain aspects of quantum measurement theory. The quantum Zeno effect is the inhibition of transitions between states by frequent measurements. (R. J. Cook, Phys. Scripta T21, 49 (1988)) We have observed this effect in the ($m_I=3/2$, $m_J=1/2$) $\leftrightarrow$ (1/2, 1/2) $^9Be^+$ ground-state rf transition. The measurements are short pulses of light tuned between the (3/2, 1/2) ground state and the $^2P_{3/2}$(3/2, 3/2) excited state. If the ion is in state, it scatters a few photons; if it is in the other, it scatters no photons. In the latter case the wavefunction collapse is due to a null measurement. (M. Porrati and S. Putterman, Phys. Rev. A36, 929 (1987)) The dynamics of this system are similar to those which are predicted to lead to nonexponential spontaneous decay at short times. Further studies of this type, perhaps with single ions, may lead to a more detailed understanding of relaxation processes.

(7.) Sympathetic cooling.

This technique, which was first suggested and demonstrated in our lab, allows the cooling of one species of ion by its Coulomb coupling to a second laser cooled species. First demonstrated by cooling Hg^+ ions by their contact with laser cooled Be^+ ions, this technique has now been routinely used to cool $^9Be^+$ ions by their contact with laser cooled Mg^+ ions.

In the $^9Be^+$ experiments, it is necessary to turn off the $^9Be^+$ cooling/optical pumping laser in order to avoid a.c. stark shifts on the $^9Be^+$ hyperfine levels caused by this laser. Without the sympathetic cooling provided by the Mg^+, the ions would quickly heat (to about 10 K in 10 s) because of plasma instabilities caused by static field asymmetries. However with the sympathetic cooling, the ions remain cold ($T \ll 1K$) essentially indefinitely. This has allowed the use of very long Ramsey interrogation times and therefore narrow linewidths. Figure 5 shows the signal obtained with a 550 s (~ 10 min) Ramsey interrogation period. This gives a linewidth of 0.0009 Hz. We have also used a Ramsey interrogation period of 30 min to obtain a 0.0003 Hz linewidth but the signal to noise is poor primarily because of the frequency instability of the reference cesium clock which controls the synthesizer.

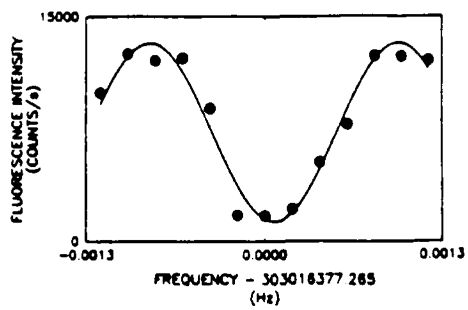

Fig. 5. Signal obtained with 3200 Be^+ ions on the field independent "clock" transition with a 550 s Ramsey free precession period. The data are the result of one sweep. The sweep width is 2.4 mHz and the frequency interval between points is 0.2 mHz. The dots are experimental and the curve is a least squares fit. A signal-to-noise ratio of 12 is estimated from the fit. The noise is caused by the frequency fluctuations of the (cesium clock) reference oscillator for the synthesizer.

(8.) Synchrotron frequency divider.

This project is so far due to the efforts of one graduate student. The trap construction is now nearly complete and should be under vacuum by summer. For demonstration purposes, this device will coherently divide 9 GHz rediation down to 3 GHz; ultimately this technique may be used to provide coherent optical to microwave frequency division. A major task this last year was the design and fabrication of an efficient coupling mechanism for the output of the electron cyclotron motion to the amplifier first stage.

(9.) Laser development.

Effort has been devoted primarily to narrowing the spectral width of a 563 nm dye laser, which when doubled to 281.5 nm is used to drive the quadrupole "clock" transition in Hg^+ (see 2 above). Last year at this time the dye laser had a linewidth of 30 kHz, this year we have seen linewidths as narrow as 100 Hz.

The main idea for this precise laser stabilization is to lock the dye laser to a very stable Fabry-Perot reference cavity using frequency modulation techniques and fast electronics. With the present electronics, the dye laser tracks to frequency of the cavity to about 0.005 hertz precision. This estimate comes from integrating the noise observed on the feedback signal. Therefore, to a very high degree, the stability of the laser is governed by the stability of the cavity. To a very good approximation, we think the Hg^+ acts as a 2 Hz bandpass filter which is stable to much better than 2 Hz. Therefore the observed linewidths (50 Hz) are a reflection of the laser stability (i.e., the stability of the reference cavity) over the time taken to trace out a resonance. These are more narrow than any reported for a visible laser.

OFFICE OF NAVAL RESEARCH

PUBLICATIONS† / PATENTS/ PRESENTATIONS / HONORS REPORT

1 October 1988 through 30 September 1989

for

Contract N00014-89-F0001

"COOLED ION FREQUENCY STANDARD"

Principal Investigator

David J. Wineland

Time and Frequency Division

National Institute of Standards and Technology

Boulder, Colorado 80303

FTS - 320-5286

(303) 497-5286

A. PAPERS PUBLISHED IN REFEREED JOURNALS (since June 1, 1988)

1. "Precise Optical Spectroscopy with Ion Traps," W.M. Itano, J.C. Bergquist, R. G. Hulet, and D. J. Wineland, Physica Scripta T22, 79 (1988).

2. "Thermal Shifts of the Spectral Lines in the $^4F_{3/2}$ to $^4I_{11/2}$ Manifold of a Nd:YAG Laser," S. Z. Xing and J. C. Bergquist, IEEE J. Quant. Electronics 24, 1829 (1989).

3. "Static Properties of a Nonneutral $^9Be^+$ Ion Plasma," L. R. Brewer, J. D. Prestage, J. J. Bollinger, W. M. Itano, D. J. Larson, and D. J. Wineland, Phys. Rev. A38, 859 (1988).

4. "Photon Antibunching and Sub-Poissonian Statistics from Quantum Jumps in One and Two Atoms," Wayne M. Itano, J. C. Bergquist, and D. J. Wineland, Phys. Rev. A38, 559 (1988).

5. "Perpendicular Laser Cooling of Ion Plasmas in a Penning Trap," Wayne M. Itano, L. R. Brewer, D. J. Larson, and D. J. Wineland, Phys. Rev. A38, 5698 (1988).

6. "Laser Cooling to the Zero Point Energy of Motion," F. Diedrich, J. C. Bergquist, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett. 62, 403 (1989).

7. "Rydberg Constant and Fundamental Atomic Physics," P. Zhao, W. Lichten, Z. Zhou, H. P. Layer and J. C. Bergquist, Phys. Rev. A39, 2888 (1989).

8. "Cooling in Traps," R. Blatt, G. Lafyatis, W. D. Phillips, S. Stenholm, and D. J. Wineland, Physica Scripta T22, 216 (1988).

9. "Test of the Linearity of Quantum Mechanics by rf Spectroscopy of the $^9Be^+$ Ground State," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert and D. J. Wineland, Phys. Rev. Lett. 63, 1031 (1989).

B. PAPERS SUBMITTED TO REFEREED JOURNALS (not yet published)

1. "The Quantum Zeno Effect in a Two-Level System," W. M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland, in preparation.

C. BOOKS (and sections thereof) PUBLISHED (Since June 1, 1988)

1. "Liquid and Solid Ion Plasmas," D. J. Wineland, W. M. Itano, J. C. Bergquist, S. L. Gilbert, J. J. Bollinger, and F. Ascarrunz, In Non-neutral Plasma Physics, ed. by C. W. Roberson and C. F. Driscoll, A.I.P. Conf. Proc. 175, (American Institute of Physics, New York, 1988), p. 93.

2. Trapped Ions and Laser Cooling II, ed. by D. J. Wineland, W. M. Itano, J. C. Bergquist, and J. J. Bollinger, NIST Technical Note 1324, 1988.

3. "Ion Trapping Techniques: Laser Cooling and Sympathetic Cooling," J. J. Bollinger, L. R. Brewer, J. C. Bergquist, W. M. Itano, D. J. Larson, S. L. Gilbert, and D. J. Wineland, in Intense Positron Beams, ed. by E. H. Ottewitte and W. Kells (World Scientific, Singapore, 1988), p. 63.

4. "Frequency Standards in the Optical Spectrum," D. J. Wineland, J. C. Bergquist, W. M. Itano, F. Diedrich and C. S. Weimer, in The Hydrogen Atom, Ed. by G. F. Bassani, M. Inguscio, and T. W. Hänsch, (Springer Verlag, Berlin, Heidelberg, 1989) p. 123.

5. "High Accuracy Spectroscopy of Stored Ions," D. J. Wineland, W. M. Itano, J. C. Bergquist, J. J. Bollinger, S. L. Gilbert, and F. Diedrich, in Frequency Standards and Metrology, Proc. Fourth Symposium, Ancona, Italy, (Springer-Verlag, Berlin, Heidelberg, 1989) p. 71.

6. "Hg^+ Single Ion Spectroscopy," J. C. Bergquist, F. Diedrich, W. M. Itano, and D. J. Wineland, ibid, p. 287.

7. "Frequency Standards Utilizing Penning Traps," J. J. Bollinger, S. L. Gilbert, W. M. Itano, and D. J. Wineland, ibid, p. 319.

8. "Quantative Study of Laser Cooling in a Penning Trap," W. M. Itano, L. R. Brewer, D. J. Larson, J. J. Bollinger, S. L. Gilbert and D. J. Wineland, ibid, p. 447.

9. "Observation of Shell Structures with Ions Stored in Traps," J. J. Bollinger, S. L. Gilbert, and D. J. Wineland, Proc. of the Workshop on Crystalline Ion Beams, Wertheim, W. Germany, Ed. by R. W. Hasse, I. Hofmann, D. Liese (GSI report GSI-89-10, ISSN 0170-4546) p.231.

10. "Coulomb Clusters of Ions in a Paul Trap," W. M. Itano, J. C. Bergquist, and D. J. Wineland, ibid, p. 241.

11. "The Digitized Atom and Optical Pumping," D. J. Wineland, W. M. Itano, J. C. Bergquist and R. G. Hulet, in Atomic Physics 11, ed. by S. Haroche, J. C. Gay, G. Grynberg, (World Scientific Press, Singapore, 1989) p. 741.

12. "Liquid and Solid Phases of Laser Cooled Ions," S. L. Gilbert, J. C. Bergquist, J. J. Bollinger, W. M. Itano, and D. J. Wineland, ibid.

D. BOOKS (and sections thereof) SUBMITTED

1. "Atomic Clocks," W. M. Itano, in McGraw-Hill Encyclopedia of Science and Technology, 7th Edition (McGraw-Hill), New York), (in press).

2. "Laser Cooling," D. J. Wineland, McGraw-Hill Encyclopedia of Science and Technology, to be published.

3. "Progress at NIST Towards Absolute Frequency Standards Using Stored Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, D. J. Heinzen, S. L. Gilbert, C. H. Manney, and C. S. Weimer, Proc. 43rd Annual Symposium on Frequency Control, Denver, June, 1989, to be published.

4. "Quantum Optics of Single, Trapped Ions," W. M. Itano, J. C. Bergquist, F. Diedrich, and D. J. Wineland, Proc. Sixth Rochester Conference on Coherence and Quantum Optics, Rochester, NY, June 1989. to be published.

5. "Test of the Linearity of Quantum Mechanics by rf Spectroscopy of the $^9Be^+$ Ground State," D. J. Heinzen, J. J. Bollinger, W. M. Itano, S. L. Gilbert, and D. J. Wineland, ibid.

6. "Observation of Correlations in Finite, Strongly Coupled Ion Plasmas," J. J. Bollinger, S. L. Gilbert, D. J. Heinzen, W. M. Itano, and D. J. Wineland, in Proc. Yamada Conf. on Strongly Coupled Plasma Physics, Tokyo, Japan, Aug. 29-Sept. 2, 1989, ed. by S. Ichimaru.

PATENTS FILED

None

PATENTS GRANTED

None

E. INVITED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES (Since Oct. 1, 1988)

1. "Liquid and Solid Plasmas." Invited Review Talk at the Division of Plasma Physics meeting of the American Physical Society, Hollywood, FL, November 1988, S. L. Gilbert.
2. "Spectroscopy and Optical Frequency Standards with a Single Ion," Spring Meeting of American Physical Society, May 1-4 1989, Baltimore, J. C. Bergquist.
3. "Hg^+ Single Ion Spectroscopy," Ninth International Conference on Laser Spectroscopy, June 1989, Bretton Wood, NH, J. C. Bergquist.
4. "Optical Spectroscopy and Laser Cooling for a Single Ion," Gordon Conference on Atomic Physics, July 1989, Wolfeboro, NH, J. C. Bergquist.
5. "Observation of Shell Structure with Ions Stored in Traps," Workshop on Crystalline Ion Beams, Wertheim/Main, Germany October 1988, J. J. Bollinger.
6. "Observations of Correlations in Finite, Strongly Coupled Ion Plasmas," Yamada Conf. on Strongly Coupled Plasmas, Yamada, Japan, Aug. 1989, J. J. Bollinger.
7. "Coulomb Clusters of Ions in a Paul Trap," Workshop on Crystalline Ion Beams, Wertheim, W. Germany, Oct. 1988, W. M. Itano.
8. "Quantum Optics of Single, Trapped Ions," 6th Rochester Conference on Coherence and Quantum Optics, July 1989, W. M. Itano.
9. "Tests of Quantum Mechanics with Laser Cooled Ions," 5th Interdisciplinary Laser Science Conference, Stanford, CA, Aug. 1989, W. M. Itano.
10. "Laser Cooled Trapped Ions," (summer school, series of 5 talks) Univ. of Sao Paulo, San Carlos, Brazil. Jan. 1989, D. J. Wineland.
11. "Quantum Jumps, Ion Crystals and Solid Plasmas," Plenary talk at QELS, Baltimore, MD, April 1989, D. J. Wineland.
12. "Ion Frequency Standards, Progress at NIST," Frequency Control Symposium, Denver, CO, May 1989, D. J. Wineland.

F. OTHER INVITED TALKS (Colloquia etc.) (Since Oct. 1, 1988)

1. Physics Colloquium, the University of Michigan, Ann Arbor, Michigan January 1989, S. L. Gilbert.
2. Physics Colloquium, the University of Maryland, College Park, MD, January 1989, S. L. Gilbert.
3. Physics Colloquium, New York University, New York, NY, February 1989, S. L. Gilbert.
4. Physics Colloquium, the University of Notre Dame, Notre Dame, Indiana, October 1988, S. L. Gilbert.
5. Physics Colloquium, the University of Colorado, Boulder, Colorado, October 1988, S. L. Gilbert.
6. Physics Colloquium, the University of Southern California, Los Angeles, CA, March, 1989, S. L. Gilbert.
7. Physics Colloquium, UCLA, Los Angeles, CA, March 1989, S. L. Gilbert.
8. Physics Colloquium, MIT, Boston, MA, March, 1989, S. L. Gilbert.
9. Physics Colloquium, Auburn, Auburn, AL, March, 1989, S. L. Gilbert.
10. Physics Colloquium, Livermore Labs, Livermore, CA, January 1989, D. J. Heinzen.
11. Physics Colloquium, Univ. of Texas, Austin, TX, April 1989, D. J. Heinzen.
12. Physics Colloquium, Inst. of Physics, Mainz, W. Germany, October 1988, W. M. Itano.
13. Physics Colloquium, Los Alamos, Los Alamos, NM, October 1988, W. M. Itano.
14. Physics Colloquium, Utah State Univ. Logan, Utah, April 1989, W. M. Itano.
15. Physics Colloquium, Univ. of Chicago, Chicago, IL, October 1988, J. J. Bollinger.
16. Physics Colloquium, Notre Dame, September 1989, J. J. Bollinger
17. Physics Colloquium, U.C.S.D., LaJolla, CA, November 1988, J. J. Bollinger.
18. Physics Colloquium, Rice Univ., Houston, TX, November 1988, D. J. Wineland.
19. Physics Colloquium, Cornell Univ., Ithaca, NY, December 1988, D. J. Wineland.
20. Physics Colloquium, IBM, Yorktown Heights, NY, December 1988, D. J. Wineland.
21. Physics Colloquium, S.U.N.Y., Stony Brook, NY, December 1988, D. J. Wineland.
22. Physics Colloquium, Stanford Univ., Stanford, CA, February 1989, D. J. Wineland.

HONORS / AWARDS / PRIZES

None

GRADUATE STUDENTS SUPPORTED UNDER CONTRACT FOR YEAR ENDING 30 SEPTEMBER 1989

Carl S. Weimer (Colorado State Univ.) (Partial support)

POSTDOCTORALS SUPPORTED UNDER CONTRACT FOR YEAR ENDING 30 SEPTEMBER 1989

Jerome Helffrich (partial support)

Daniel Heinzen (partial support)

Mark Raizen (partial support)

Fred Moore (partial support)